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WHERE IS THE MOLECULAR HYDROGEN IN DAMPED LY α ABSORBERS?

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ABSTRACT

We show in this paper why molecular millimeter absorption line searches in DLAs have been unsuccessful. We use CO emission line maps of local galaxies to derive the $\mathrm{H_2}$ column density distribution function $f(N_{\mathrm{H_2}})$ at $z = 0$. We show that it forms a natural extension to $f(N_{\mathrm{HI}})$: the $\mathrm{H_2}$ distribution exceeds $f(N_{\mathrm{HI}})$ at $N_H \approx 10^{22}\mathrm{cm}^{-2}$ and exhibits a power law drop-off with slope ~ -2.5. Approximately 97% of the $\mathrm{H_2}$ mass density $\rho_{\mathrm{H_2}}$ is in systems above $N_{\mathrm{H_2}} = 10^{21}\,\mathrm{cm}^{-2}$. We derive a value $\rho_{\mathrm{H_2}} = 1.1 \times 10^7 h_{70}\,\mathrm{M_\odot Mpc^{-3}}$, which is $\approx 25\%$ the mass density of atomic hydrogen. Yet, the redshift number density of $\mathrm{H_2}$ above this $N_{\mathrm{H_2}}$ limit is only $\approx 3 \times 10^{-4}$, a factor 150 lower than that for H I in DLAs at $z = 0$. Furthermore, we show that the median impact parameter between a $N_{\mathrm{H_2}} > 10^{21}\,\mathrm{cm}^{-2}$ absorber and the centre of the galaxy hosting the $\mathrm{H_2}$ gas is only 2.5 kpc. Based on arguments related to the Schmidt law, we argue that $\mathrm{H_2}$ gas above this column density limit is associated with a large fraction of the integral star formation rate density. Even allowing for an increased molecular mass density at higher redshifts, the derived cross-sections indicate that it is very unlikely to identify the bulk of the molecular gas in present quasar absorption lines samples. We discuss the prospects for identifying this molecular mass in future surveys.

Subject headings: galaxies: ISM — ISM: molecules — ISM: atoms — quasars: absorption lines

1. INTRODUCTION

At high redshift, the atomic hydrogen is well surveyed through observations of damped Lyα systems (DLAs), quasar absorption line systems characterized by $N_{\mathrm{HI}} > 2 \times 10^{20}\,\mathrm{cm}^{-2}$ (e.g., Prochaska et al. 2005). These observations yield the frequency distribution of H I surface density $f(N_{\mathrm{HI}})$ and the first moment gives the cosmological mass density of predominantly neutral, atomic gas. Several small surveys have been performed to search for molecular gas associated with DLAs. Yet, there have been no positive detections of CO and other molecules in millimeter wavelength absorption line searches (Curran et al. 2004, and references therein). Searches for $\mathrm{H_2}$ absorption in DLAs (via the Lyman and Werner bands) show a success rate of only $\approx 20\%$ and even these sightlines have low molecular fractions (Ledoux et al. 2003).

These low detection rates have drawn into question the relationship between DLAs and star formation at high redshift (e.g. Hopkins et al. 2005). Other galaxy surveys have shown that star formation is very active at these epochs (e.g., Steidel et al. 1999). Presumably, since stars form in molecular clouds, these star forming galaxies have significant molecular gas mass that has not been discovered through quasar absorption line studies. The obvious conclusion, then, is that these molecular regions have very low covering fraction on the sky and/or contain sufficient columns of dust to obscure any background quasar.

In this paper we address these issues by making use of the studies of the CO distribution in nearby galaxies. Zwaan et al. (2005b) recently showed that most DLA properties (luminosities, impact parameters between quasars and DLAs, and metal abundances) are consistent with them arising in galaxies like those in the local universe. Building on this result, we use here information on the molecular content of nearby galaxies, to make predictions of the detectability of $\mathrm{H_2}$ in DLAs. The $\mathrm{H_2}$ distribution in nearby galaxies is generally derived through mapping of the CO(1–0) line at a frequency of 115 GHz. The $\mathrm{H_2}$ column densities derived from these observations are typically higher than $5 \times 10^{20}\,\mathrm{cm}^{-2}$, which is very close to those reached by millimeter CO absorption line observations in redshifted DLAs against radio-loud background sources.

2. THE $\mathrm{H_2}$ CROSS-SECTION

The largest sample of high spatial resolution CO(1–0) maps of nearby galaxies is the BIMA SONG sample presented by Helfer et al. (2003). The sample consists of 44 optically selected galaxies with Hubble types Sab to Sd at a median distance of 11.9 Mpc, and is selected without reference to CO or infrared brightness. The fact that this sample does not include early types and irregulars is not expected to introduce an important bias in our calculations. CO has been detected in a number of elliptical galaxies (Young 2002), but their contribution to the total $\mathrm{H_2}$ mass density is expected to be minimal. Irregulars contribute approximately 20% to the total H I mass density (Zwaan et al. 2003), but their ratio of $\mathrm{H_2}$ mass to H I mass is down by almost a factor ten compared to the average over all galaxy types (Young & Knezek 1989), which implies that their contribution to the $\mathrm{H_2}$ mass density is also marginal. We refer to Zwaan et al. (2005b) for a discussion on why optically selected galaxies are a fair sample to compare with absorption line statistics.

We used the combined interferometric and single dish maps to calculate $\mathrm{H_2}$ column density maps, using a CO/$\mathrm{H_2}$ conversion factor of $2.8 \times 10^{20}\,\mathrm{cm}^{-2}(\mathrm{K\,km\,s^{-1}})^{-1}$ (Kennicutt 1998). Helfer et al. (2003) report that the lowest significant isolated $\mathrm{H_2}$ densities at 3σ in these maps are approximately $13.7\,\mathrm{M_\odot\,pc^{-2}}$, which corresponds to an $N_{\mathrm{H_2}}$ limit of $8.5 \times 10^{20}\mathrm{cm}^{-2}$. The typical spatial resolution of the $6''$ beam is 350 pc at the median distance of the sample.

We calculate the $\mathrm{H_2}$ column density distribution $f(N_{\mathrm{H_2}})$ using a method analogous to that for H I set out by

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Zwaan et al. (2005b):

$$f(N_{\rm H_2}) = \frac{c}{H_0}\frac{\sum_i \Phi(M_{Bi})w(M_{Bi})A_i(\log N_{\rm H_2})}{N_{\rm H_2}\ \ln 10\,\Delta\log N_{\rm H_2}}. \qquad (1)$$

Here, $\Phi(M_{Bi})$ is the space density of galaxy i measured through the optical luminosity function as measured by Norberg et al. (2002), with Schechter parameters: $M_B^* - 5\log h_{70} = -20.43$, $\alpha = -1.21$, and $\Phi^* = 5.5 \times 10^{-3} h_{70}^3 \mathrm{Mpc}^{-3}$. The function $w(M_{Bi})$ is a weighting function that takes into account the varying number of galaxies across the full stretch of M_B, and is calculated by taking the reciprocal of the number of galaxies in the range $M_{Bi} - \Delta/2$ to $M_{Bi} + \Delta/2$, where Δ is taken to be 0.25. $A_i(\log N_{\rm H_2})$ is the area function that describes for galaxy i the area in Mpc^2 corresponding to a column density in the range $\log N_{\rm H_2}$ to $\log N_{\rm H_2} + \Delta\log N_{\rm H_2}$. In practice, this is simply calculated by summing for each galaxy the number of pixels in a certain $\log N_{\rm H_2}$ range multiplied by the physical area of a pixel. Finally, c/H_0 converts the number of systems per Mpc to that per unit redshift.

The BIMA SONG galaxies are selected to be less inclined than 70°. In order to achieve a $f(N)$ measurement for randomly oriented galaxies, we de-projected all galaxies to face-on assuming that the H_2 gas is optically thin, and subsequently recalculated the column density distribution function for ten inclinations i evenly spaced in $\cos(i)$ between 0 and 1. The final $f(N_{\rm H})$ was taken to be the average of these ten distribution functions. This procedure only makes a small modification to the $f(N_{\rm H})$ calculated from the H_2 distributions uncorrected for inclination effects.

Figure 1 shows the resulting column density distribution function $f(N_{\rm H_2})$, together with $f(N_{\rm HI})$ from Zwaan et al. (2005b). We note that the horizontal axis represents the atom surface density, which in the case of H_2 is equal to $2N_{\rm H_2}$. The errorbars are 1σ uncertainties and include counting statistics and the uncertainty in the optical luminosity function. The uncertainty in the CO/H_2 conversion factor could introduce the largest error in our $f(N_{\rm H_2})$. The horizontal errorbar indicates the uncertainty in $f(N_{\rm H_2})$ if this conversion factor is uncertain by 50%. The $f(N_{\rm H_2})$ can be fitted very well with a log-normal distribution: $f(N) = f^* \exp -[(\log N - \sigma)/\mu]^2/2$, where $\mu = 20.6$, $\sigma = 0.65$ and the normalization f^* is $1.1\times10^{-25}\,\mathrm{cm}^2$. The distribution function of H_2 column densities seems to follow a natural extension of the H I distribution function, in such a way that the summed $f(N_{\rm H})$ roughly follows a power-law distribution $N_{\rm H}^{-2.5}$ between $\log N_{\rm H} = 21$ and $\log N_{\rm H} = 24$. The two distribution functions cross at $\log N_{\rm H} \approx 22$, which is the approximate column density associated with the conversion from H I to H_2 (e.g. Schaye 2001).

By taking the integral over $f(N_{\rm H_2})$ multiplied by $N_{\rm H_2}$, we find the total H_2 mass density at $z = 0$ to be $\rho_{\rm H_2} = 1.1 \times 10^7 \mathrm{M}_\odot\,\mathrm{Mpc}^{-3}$, which is approximately one quarter of $\rho_{\rm HI}(z = 0)$ (Zwaan et al. 2005a). Keres et al. (2003) found $\rho_{\rm H_2} = (2.0 \pm 0.7) \times 10^7 \mathrm{M}_\odot\,\mathrm{Mpc}^{-3}$, where we converted their value to $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and used the same CO/H_2 conversion factor as we used. This difference might be partly due to the fact that the BIMA SONG sample does not include many dwarf galaxies, although judging from the Keres et al. (2003) CO mass function, these galaxies contribute only very little to $\rho_{\rm H_2}$. Another reason could be that the BIMA SONG sample is optically selected, whereas Keres' sample (Young & Knezek 1989) predominantly consists of FIR-selected galaxies, which can cause a bias toward CO-rich galaxies (see e.g., Solomon & Sage 1988). Casoli et al. (1998) used a larger sample than Young & Knezek (1989), and took into account CO non-detections, to find much lower values of $M_{\rm H_2}/M_{\rm HI}$, which are fully consistent with our derived value of $\rho_{\rm H_2}/\rho_{\rm HI}$.

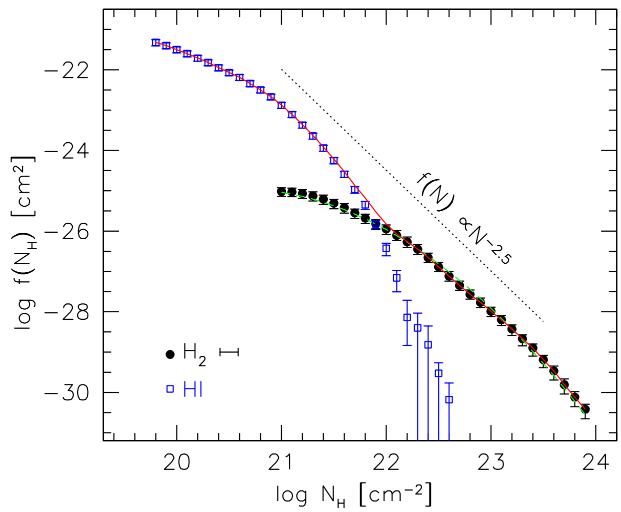

FIG. 1.— The column density distribution function of H I and H_2 at $z = 0$. The H I curve is adopted from Zwaan et al. (2005b), the H_2 curve is measured from the CO emission line maps from the BIMA SONG sample. Column densities are expressed in atoms per cm^2, also for H_2. The solid line is the summed $f(N_{\rm H})$. The horizontal errorbar indicates the uncertainty in $f(N_{\rm H_2})$ if the CO/$N_{\rm H_2}$ conversion factor is uncertain by 50%. The $f(N_{\rm H_2})$ can be fitted very well with a log-normal distribution, where $\mu = 20.6$, $\sigma = 0.65$ and the normalization is $1.1 \times 10^{-25}\,\mathrm{cm}^2$, as indicated by the dashed line.

What fraction of the cosmic H_2 mass density do we miss below the $N_{\rm H_2}$ detection limit of $8.5\times10^{20}\mathrm{cm}^{-2}$? The $f(N_{\rm H_2})$ appears to flatten off at the lowest column densities, which implies that the contribution of low $N_{\rm H_2}$ is low, unless the $f(N_{\rm H_2})$ rises steeply below our detection limit. To test this, we make use of the H_2 absorption line survey in DLAs by Ledoux et al. (2003). These authors report a detection rate of 13 to 20%, with H_2 column densities typically in the range $\log N_{\rm H_2} = 17$ to 18.5. Based on their statistics and the measured $f(N_{\rm HI})$ of DLAs at $z = 0$ from Zwaan et al. (2005b), we estimate that $\log f(N_{\rm H_2} = 10^{18}\mathrm{cm}^{-2}) = -23.5$ at $z = 0$, conservatively assuming that the detection statistics of H_2 absorption has not evolved since $z \approx 2$. Extrapolating our measured $f(N_{\rm H_2})$ to this value, we find that $f(N_{\rm H_2}) \propto {N_{\rm H_2}}^{-0.5}$ (see Figure 2). Now, by integrating $\int N_{\rm H_2} f(N_{\rm H_2}) dN_{\rm H_2}$ we find the total H_2 mass as a function of $N_{\rm H_2}$. From this we derive that the mass contained in systems $\log N_{\rm H_2} < 21$ is only 3% of the total H_2 mass density. This implies that our results presented in this paper apply to roughly 97% of the total number of H_2 molecules in the universe.

Beam smearing might lead to an overestimation of the cross-sections at low $N_{\rm H_2}$ and an underestimte of $f(N_{\rm H_2})$ at large $N_{\rm H_2}$. Because a main result of the next section is that the H_2 cross-sections are small, we have ignored these effects for now.

3. WHERE TO FIND THE MOLECULES

The redshift number density dN/dz of H_2 above the $N_{\rm H_2}$ limit of $10^{21}\ \mathrm{cm}^{-2}$ can be calculated from $f(N_{\rm H_2})$ by summing over all column densities larger than this limit. We find

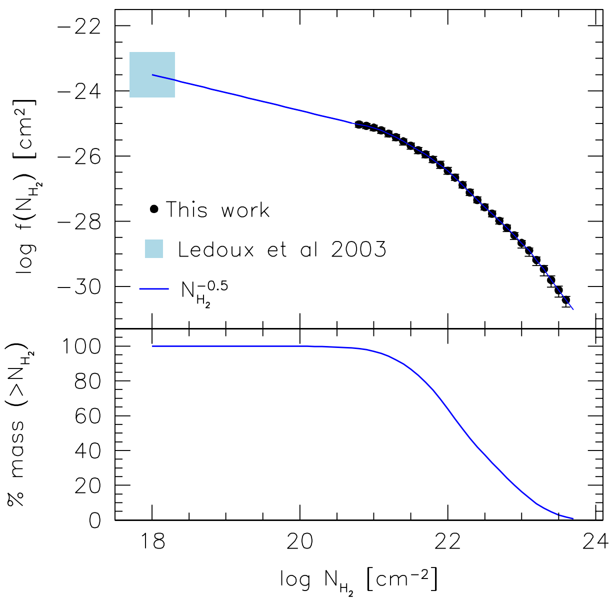

FIG. 2.— *Top:* The column density distribution function of H_2, where the circles show $f(N_{H_2})$ at $z=0$ derived from the BIMA SONG CO maps, and the grey square indicates the value at much lower column densities, estimated from the H_2 absorption data from Ledoux et al. (2003). These latter data are from systems at redshifts $z \approx 2$, which implies that the derived $f(N_{H_2})$ point is probably an upper limit. *Bottom:* The cumulative H_2 mass distribution in column densities $> N_{H_2}$. Here, we have includes the $N_{H_2}{}^{-0.5}$ extension as shown in the top panel. Approximately 97% of the H_2 molecules are in column densities $N_{H_2} > 10^{21}\,\mathrm{cm}^{-2}$.

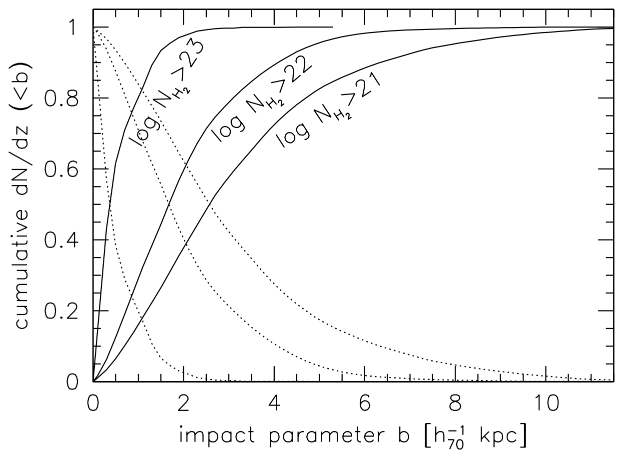

FIG. 3.— The normalized $z=0$ cumulative distribution function of impact parameters of H_2 cross-section selected systems above different H_2 column density limits. The solid is the distribution for impact parameters $< b$, the dotted line for $> b$.

that $dN/dz = 3\times10^{-4}$, which is approximately 150 times lower than the corresponding value for H I above the DLA limit (Zwaan et al. 2005b). Taking this result at face value, this would imply that at $z=0$ only one in every ~ 150 DLAs is expected to show strong CO absorption lines.

In Figure 3 we show how close to the centre of galaxies high column density H_2 is to be found. This figure shows the normalized cumulative distribution function of impact parameters between the centers of galaxies and the positions where the H_2 absorption is measured. We constructed this diagram from the BIMA SONG CO maps, and using a weighting scheme similar as discussed for the evaluation of $f(N_{H_2})$. Apparently, the median impact parameter at which an $N_{H_2} > 10^{21}\,\mathrm{cm}^{-2}$ absorber is expected is only 2.5 kpc and 90% of the cross-section is at impact parameters smaller than 6.5 kpc. For higher H_2 column densities, these impact parameters are even smaller. Applying these findings to the DLA population, millimeter CO observers need to select those DLAs that arise within 2.5 kpc of the centers of galaxies to have a 50% probability of identifying an absorption line corresponding to $N_{H_2} > 10^{21}\,\mathrm{cm}^{-2}$. None of the *identified* DLA host galaxies have such small impact parameters, except perhaps two cases studied by Rao et al. (2003) for which only upper limits to the impact parameters could be given due to blending with the background quasar light.

Our conclusions are qualitatively supported by observations of redshifted molecular lines. To date, only four redshifted molecular absorbers have been identified (Wiklind & Combes 1999, and references therein), two of which arise in gravitationally lensed intervening galaxies and two originate in the galaxy that also hosts the radio source against which the absorption is seen. In all cases the sightline through the high H_2 column passes through the galaxies at small impact parameters.

These cross-section arguments already explain the very low detection rate of molecules in DLAs, but there are additional effects that hinder the detection of molecules. Molecular hydrogen forms on the surface of dust grains. The regions in galaxies containing most of the universe's H_2 molecules are therefore likely to be dusty, causing a higher optical extinction of the background sources, which, in turn, might lead to them dropping out of magnitude-limited surveys. Obviously, radio-selected quasars do not suffer from this bias and are potentially good candidates against which to find high N_{H_2} absorbers. However, $dN/dz(N_{H_2})$ is so low that identifying such an absorber is highly unlikely in current radio-selected quasars samples. For example, the redshift interval covered by the CORALS survey (Ellison et al. 2001) of radio-loud quasars is only $\Delta z = 55$ for Lyα, corresponding to $\Delta z \approx 100$ for H_2. The redshift interval required for identifying a high N_{H_2} absorber should be on the order of $(dN/dz)^{-1} = 3300$ at $z=0$, or approximately 600 at $z = 2-3$, taking into account the cosmological variation of the absorption distance interval dX. Using this method to obtain sufficient statistics to measure the molecular mass density at intermediate and high redshifts, would require radio source samples larger than currently available.

Finally, we address the question whether there might exist a significant amount of H_2 gas not associated with DLAs. CO mapping of nearby galaxies has shown that many galaxies show a depression in the H I distribution where the H_2 column densities are highest (see e.g. Wong & Blitz 2002). Presumably, in regions where the molecular densities are highest, most of the H I has been converted to H_2. We use the H I and CO maps of seven nearby galaxies studied by Wong & Blitz (2002) to test how much H_2 exists below the H I DLA limit. We compare the H I and CO maps smoothed to the same spatial resolution of 13″ to 23″, and find that the mass fraction of H_2 in regions where $N_{HI} < 2\times10^{20}\,\mathrm{cm}^{-2}$ ranges from 0 to 40%. Averaged over all pixels from the total sample, this fraction is 6%. In many cases the fraction is underestimated

because the highest N_{H_2} is smoothed over larger regions. Of course, this small sample may not be representative of the total galaxy population at $z = 0$, but at least this exercise shows that a small fraction of the cosmic H_2 density must be found in sub-DLAs. One might identify such absorbers by searching for a sub-DLAs with abnormally high metallicities, i.e. this could indicate absorbers where the hydrogen is not predominantly atomic. An example of a high metallicity sub-DLA has recently been found by Péroux et al. (2006).

4. IMPLICATIONS FOR THE STAR FORMATION RATE DENSITY

Lanzetta et al. (2002) and Hopkins et al. (2005) recently estimated the star formation rate density (SFRD) in DLA systems by applying the 'Schmidt law' of star formation to the H I column density distribution function $f(N_{HI})$. The Schmidt law is defined in local galaxies and states that the star formation rate correlates very well with total neutral gas surface density $\Sigma_{HI} + \Sigma_{H_2}$ to the power 1.4, as was demonstrated by Kennicutt (1998). Here, we wish to investigate whether the SFRD measurements based on H I alone give meaningful results, or whether H_2 should be taken into account for a reliable SFRD measurement. Since presently we only know $f(N_{H_2})$ at $z = 0$, we cannot improve the measurements of Hopkins et al. (2005) at high redshift by including H_2. Our aim is simply to test the validity of the method and discuss the implications of including molecules.

We start with estimating what fraction of the SFRD is actually contributed by those regions where the H_2 column is higher than the H I column. To this end, we make use of Equation 4 from Hopkins et al. (2005) that relates the SFRD to the $f(N_H)$, and apply it to our measurement of $f(N_{H_2})$, and $f(N_{HI})$ from Zwaan et al. (2005b). We make one important modification in that we convert our $z = 0$ gas densities to those that would be observed if the gas disks were observed 'face-on', assuming that the H I and H_2 layers are optically thin. At $z = 0$ the $f(N_H)$ is a result of a randomly oriented population of galaxies and it is easy to see that the highest column densities are mostly the result of highly inclined disks. However, the Schmidt law is valid for face-on gas densities. De-projecting the disk implies that the surface area increases but the column densities decrease. The net result is that that the $f(N_H)$ as it is normally defined will overestimate the SFRD. At $z = 0$, we find that the SFRD is overestimated by $\sim 40\%$ if the regular $f(N_H)$ is used, instead of the de-projected $f(N_H)$ for face-on disks. The de-projected $f(N_H)$ follows a nearly exponential behaviour between $\log N_H = 20.5$ and $\log N_H = 23.5$, and can be fitted with the simple equation $f(N_H) = 2 \times 10^{29} N_H^{-2.5}$.

Our results are presented in Fig. 4, which shows the implied SFRD as a function of H I and H_2 face-on column density. We see that the H I and H_2 column densities contribute approximately equally to the total SFRD. The other conclusion from this exercise is that the total derived SFRD at $z = 0$ is much higher than that derived from Hα and [OII] measurements [$\dot{\rho}_*(z = 0) \approx 0.02 M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$, Hopkins 2004]. This contradicts the findings of Hopkins et al. (2005) who conclude that at $z = 0$ the SFRD $\dot{\rho}_*$ derived from the Schmidt law and the measured $f(N_{HI})$ agrees well with the direct measurements. The origin of this contradiction is that Hopkins et al. (2005) used the $f(N_{HI})$ measurements of Ryan-Weber et al. (2003), which were later corrected upwards with a factor 3. If we use the corrected values (Ryan-Weber et al. 2005) or the measurement from Zwaan et al. (2005b), we find that $\dot{\rho}_*(z = 0) = 0.035 M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$, a factor two higher than the median of the directly measured values at $z = 0$. Using the more realistic face-on $f(N_H)$, and including both H I and H_2 in the analysis, we find that $\dot{\rho}_*(z = 0) = 0.044 M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$, also higher than the nominal value at $z = 0$. Based on the face-on $f(N_{H_2})$ only, we find $\dot{\rho}_*(z = 0) = 0.022 M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$, in good agreement with the direct measurements (see also Wong & Blitz 2002).

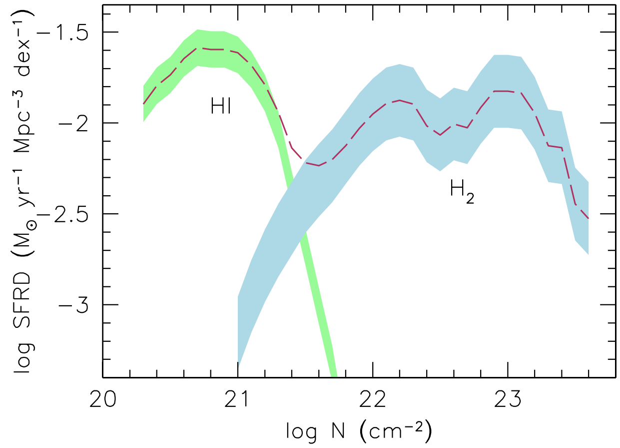

FIG. 4.— The implied star formation rate density as a function of face-on H I and H_2 column density as derived from the Kennicutt (1998) star formation law. Grey areas indicate approximate uncertainties.

Why is the value of $\dot{\rho}_*$ at $z = 0$ overestimated by a factor $2 - 3$ when derived using the $f(N_H)$ and the Schmidt law? The answer lies in the fact that the Schmidt law is defined for the 'star-forming disks', and not for the regions of the H I layer outside this area. It was shown by Kennicutt (1989) that star formation only occurs when the gas density exceeds the critical threshold density, which depends on the velocity dispersion of the gas and the galaxy's rotation curve shape and amplitude. From the $f(N_H)$ alone it is impossible to determine what the critical threshold gas density is, because this density varies between galaxies and within galaxies. Therefore, applying the Schmidt law to all regions in the local universe where the N_{HI} exceeds $\sim 10^{20}\,\mathrm{cm}^{-2}$ will grossly overestimate $\dot{\rho}_*$. [As an extreme example, consider NGC 2915, (Meurer et al. 1996) where the HI disk is many times larger than the optical disk.]

Furthermore, within galaxies the areas with the highest SFRs are often mostly molecular, and in some cases N_{HI} declines in regions of high SFR (Martin & Kennicutt 2001; Rownd & Young 1999; Wong & Blitz 2002). In regions where $\log N_{H_2} > 21$ the critical density is typically exceeded. Consequently, for the purpose of estimating $\dot{\rho}_*$, the $f(N_{H_2})$ is probably a more reliable estimator, whereas $f(N_{HI})$ only gives an upper limit to that fraction of $\dot{\rho}_*$ contributed by regions that are mostly atomic.

In our analysis we treat the H I and H_2 independently. Ideally, we would use H I and H_2 measurements from the same large galaxy sample, but unfortunately such a sample is not available. Our analysis probably slightly *under*estimates the total SFRD: in regions where the H I and H_2 columns are equal, the SFR would be $2^{1.4}/2 = 1.3$ times higher if it were derived from the summed gas density instead of from the in-

dividual densities. In most regions, where the two column densities are different, the SFR is underestimated by a much smaller fraction if the H I and H_2 are treated independently.

In summary, we have shown here that $f(N_{\rm HI})$ cannot be used to derive a meaningful SFRD at $z = 0$ and therefore probably also not at higher redshifts. Only in the unlikely situation that DLA galaxies were truly molecule free, the $f(N_{\rm HI})$ method would give a meaningful upper limit to the SFRD contributed by DLAs. Interestingly, the *shape* of $f(N_{\rm HI})$ has not evolved[3] between $z = 4$ and $z = 0$ (cf. Zwaan et al. 2005b; Prochaska et al. 2005), only the *normalization* (i.e., $\Omega_{\rm HI}$) has decreased with approximately a factor two. Based on the Hopkins et al. (2005) parameterization, this implies that $\dot{\rho}_*$ as measured through DLAs also has dropped only approximately a factor two over this redshift range. This is clearly at odds with the observations, unless one is willing to assume that the systems holding the bulk of the neutral gas account for only a small fraction of the cosmic SFRD. Furthermore, even at $z = 0$ the SFRD is dominated by regions where $N_{\rm H_2}$ exceeds $N_{\rm HI}$ (see also Wong & Blitz 2002). Given the observational fact that $\dot{\rho}_*$ evolves much faster than $\Omega_{\rm HI}$, this implies that the cosmic H_2 mass density was much higher in the past, or the laws of star formation were different.

In any case, the contention of Hopkins et al. (2005) that DLAs cannot make up for the observed SFRD at high redshift should be reviewed. Clearly, to evaluate the SFRD contributed by DLAs one should take into account their molecular content, which we have shown in the previous paragraph is extremely difficult to determine. In the absence of a measurement of $f(N_{\rm H_2})$ at higher redshifts, more direct approaches such as the CII* method (Wolfe et al. 2003) or models of the star formation history (Dessauges-Zavadsky et al. 2003) are probably more useful in constraining $\dot{\rho}_*$ from DLAs.

5. CONCLUSIONS

We have used observations of CO in nearby galaxies to make predictions on the detection rate of H_2 in DLAs. We derived a column density distribution function $f(N_{\rm H_2})$ and find that it forms a natural extension of $f(N_{\rm HI})$ at higher hydrogen column densities. The inferred redshift number density dN/dz of $N_{\rm H_2} > 10^{21}\,{\rm cm}^{-2}$ is 3×10^{-4}, which is a factor 150 lower than the corresponding number for DLAs. This implies that of the total number of DLAs currently known, only a handful are expected to show high column density molecular absorption lines. This absorption is expected to arise at impact parameters smaller than 6.5 kpc in 90% of the cases. Approximately 97% of the cosmic H_2 mass density resides in this dense, central gas, which also is associated with the bulk of the cosmic star formation rate density $\dot{\rho}_*$. The detectability of this molecular gas is further reduced by the facts that *i)* the high column density H_2 is likely associated with high dust columns, which obscures background quasars and could take them out of magnitude-limited surveys, and *ii)* a small fraction ($\lesssim 10\%$) of the H_2 is associated with sub-DLA Lyα absorption.

We apply the Schmidt law for star formation to $f(N_{\rm H_2})$ and $f(N_{\rm HI})$ and find that molecules should be taken into account to derive meaningful values for the cosmic star formation rate density $\dot{\rho}_*$. Even though the cross section of high column density H_2 is low, this gas is associated with a large fraction of $\dot{\rho}_*$. Since the molecular gas is difficult to detect in absorption, the method of using the Schmidt law and $f(N_{\rm H})$ to derive $\dot{\rho}_*$ remains of limited use.

The cold atomic gas content of the universe at redshifts $z \sim 1 - 5$ has successfully been determined from blind surveys for DLA absorbers. What are the prospects for measuring the molecular mass density at intermediate and high redshifts using similar techniques? With present technology blind molecular absorption line surveys against radio-loud background sources seem difficult given the required redshift interval. The prospects for future instruments seem better. For example, with the Atacama Large Millimeter Array[4] (ALMA) the CO(3–2) line corresponding to $\log N_{\rm H_2} > 21$ should be detectable at $z = 2$ to 3 in one minute against a 50 mJy background source. A survey of several days should be able to turn up a useful number of high $N_{\rm H_2}$ absorbers. Such a survey would by simultaneously sensitive to HCO^+ (a good H_2 tracer) at lower redshifts. The Square Kilometer Array[5] (SKA) should be able to detect the CO(1–0) and HCO^+(1–0) lines at redshifts $z > 3.6$ and > 2.6, respectively. The expected noise levels are much lower than for ALMA, implying that this instrument will be ideal for high-z molecular absorption line surveys, giving good statistics for measuring $\Omega_{\rm H_2}$.

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[3] Note however that Rao et al. (2005) find a much flatter $f(N_{\rm HI})$ distribution at $0.1 < z < 1.7$, based on MgII-selected systems.

[4] http://www.alma.info/

[5] http://www.skatelescope.org/

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